NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-SET-158**

Disposable Multi-Sensor Unattended Ground Sensor Systems for Detecting Personnel

(Systèmes de détection multi-capteurs terrestres autonome destinés à détecter du personnel)

This Report documents the findings of Task Group 158.

Published February 2015

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The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Disposable Multi-Sensor Unattended Ground Sensor Systems for Detecting Personnel

(STO-TR-SET-158)

Executive Summary

The scope of the effort conducted by the Task Group (SET-158 RTG) on *Disposable Multi-Sensor Unattended Ground Sensor Systems for Detecting Personnel* identifies and accesses potential technologies for detection of people that improves security for wide area situational awareness in open terrain operations. While the results are applicable to the urban environment, the effort focused on remote desert environments that included well-known false targets, primarily animals. The effort took advantage of existing research programs on sensor systems and as well as novel sub-systems components for personnel detection. The primary sub-system components include sensing elements, signal processing and fusion algorithms. Phenomenology aspects were the primary driver in each of these components.

This work addresses the ever-increasing demand for remote, robust and high-performance sensor systems for surveillance and target acquisition on the battlefield. The Task Group placed emphasis on low-cost unattended sensor technologies to support the need for large quantities of inexpensive multi-sensor UGS to detect personnel. The focus of the research is to develop robust signal processing and fusion algorithms using low-cost multi-sensor, non-imaging and imaging sensor nodes distributed along a remote border to detect personnel and animals.

The goal and objectives set forth were carried out in two phases. First was to identify sensors that align with the ideas of low cost, robust and data output capable of personnel and animal detection and characterization. This was accomplished using national surveys and a review of personnel detection sensors dating back to the conflict in Southeast Asia between the years of 1956 – 1975. The sensors included in the group's effort include audio and ultrasonic microphones, geophones, passive infrared, magnetometers, radar and sonar, pyroelectric array profilers and both low- and high-resolution cameras. In the second phase, sensor phenomenology and signal processing approaches were reviewed and developed at the individual sensor level. An international data collection field exercise held in March of 2012 on the SW US border was well attended by participating Nations. This included SASNet from Canada and Pearls of Wisdom system from Israel operated in conjunction with ARL personnel. The primary objectives of the trial were to provide opportunities for the collection of phenomenological data and to make data available for algorithm testing.

SET-158 Task Group met on numerous occasions beginning with the initial kick-off meeting held at the RTO office in Paris Spring of 2010. Two additional technical committee meetings were held after the PBM meetings in Greece, October 2010 and Quebec City, May 2012. SET-158 co-sponsored the 4th technical meeting with SET-TG-153 and SET-TG-142 in Cardiff, Wales, on 11 October 2011. An additional three committee meetings were held in conjunction with data collection field trials and workshops.

The committee organized two personnel detection workshops that were held in the USA. Both of these were in conjunction with the US Army Research Laboratory. These activities were well attended with numerous papers on personnel detection being presented. More than two dozen peer-reviewed papers have been published as a result of the committee activities.

Systèmes de détection multi-capteurs terrestres autonome destinés à détecter du personnel

(STO-TR-SET-158)

Synthèse

Les travaux menés par le groupe de travail « Systèmes de détection multi-capteurs terrestres autonome destinés à détecter du personnel » (SET-158 RTG) identifient et accèdent aux technologies potentielles de détection des personnes, qui améliorent la sécurité par l'appréciation de situation de zones étendues dans les opérations en terrain découvert. Même si les résultats peuvent s'appliquer à l'environnement urbain, les recherches se sont concentrées sur les environnements désertiques reculés comportant de faux objectifs bien connus, principalement des animaux. Les travaux ont tiré parti des programmes de recherche existants sur les systèmes de détection et sur les tout nouveaux composants de sous-systèmes de détection de personnel. Les principaux composants des sous-systèmes incluent les éléments de détection, le traitement du signal et les algorithmes de fusion. Les aspects de phénoménologie ont été le principal moteur de chacun de ces composants.

Ce document répond à la demande sans cesse croissante de systèmes de détection à distance, qui soient robustes et de haute performance afin d'assurer la surveillance et l'acquisition des objectifs sur le champ de bataille. Le groupe de travail a insisté sur les technologies de détection autonomes à faible coût afin de répondre au besoin de grandes quantités de capteurs terrestres autonomes (UGS) peu onéreux à multiples capteurs servant à la détection de personnel. L'objet des recherches est d'élaborer des algorithmes robustes de fusion et de traitement du signal utilisant des nœuds de multiples capteurs imageurs et non imageurs peu coûteux répartis sur une frontière éloignée pour détecter des personnes et des animaux.

Les objectifs énoncés ont été réalisés en deux phases. La première a consisté à identifier les capteurs qui correspondent au faible coût, à la robustesse et à la production de données permettant de détecter et caractériser les personnes et les animaux. Cela a été réalisé en utilisant des enquêtes nationales et une étude des capteurs de détection de personnel remontant au conflit en Asie du Sud-Est entre 1956 et 1975. Les capteurs étudiés par le groupe de travail ont été les microphones audio et ultrasonores, les géophones, les capteurs passifs à infrarouge, les magnétomètres, les radars et sonars, les profileurs à matrice pyroélectrique et les caméras basse et haute résolution. Dans la seconde phase, des approches de phénoménologie des capteurs et de traitement du signal ont été examinées et développées au niveau de chaque capteur. Un exercice international de combat à simple action visant à recueillir des données a eu lieu en mars 2012 à la frontière sud-ouest des Etats-Unis ; il a réuni beaucoup d'entités des pays participants. Ont notamment été présents le SASNet du Canada et le système Pearls of Wisdom d'Israël, opéré en lien avec le personnel de l'ARL. Les principaux objectifs de l'essai étaient de donner l'occasion de collecter des données phénoménologiques et de fournir des données pour l'essai d'algorithmes.

Le groupe de travail SET-158 s'est réuni en de nombreuses occasions, à commencer par la réunion inaugurale qui s'est tenue au sein de la RTA à Paris, en avril 2010. Deux autres réunions ont eu lieu après les réunions de la commission SET en Grèce, en octobre 2010, et à Québec, en mai 2012. Le SET-158 a organisé la quatrième réunion technique en association avec le groupe de travail SET-153 et le groupe de travail SET-142 à Cardiff, le 11 octobre 2011. Trois réunions supplémentaires ont eu lieu en relation avec les essais de recueil de données sur le terrain et les séminaires.

La commission a organisé deux séminaires portant sur la détection de personnel aux Etats-Unis, en lien avec le laboratoire de recherche de l'armée de terre des Etats-Unis. Ces activités ont attiré bon nombre de participants et de nombreux travaux sur la détection de personnel ont été présentés. Plus de deux douzaines d'articles approuvés par des pairs ont été publiés à l'issue des activités de ce groupe.

DISPOSABLE MULTI-SENSOR UNATTENDED GROUND SENSOR SYSTEMS FOR DETECTING PERSONNEL

Dr. James Sabatier[1] and Dr. Thyagaraju Damaria[2]

1.0 INTRODUCTION

The effort conducted by the Task Group (SET-158 RTG) on *Disposable Multi-Sensor Unattended Ground Sensors Systems for Detecting Personnel* identified and accessed technologies to detect personnel that improved security in wide area situational awareness in open terrain operations. Existing research programs on sensor systems for personnel detection, as well as novel sub-systems components for personnel detection, were of primary interest. Sub-system components include sensing elements, signal processing and fusion algorithms. Phenomenology aspects of the sensors, the environment and the physics of human motion detection were the primary drivers of the research.

Large quantities of inexpensive, unattended ground sensors to detect personnel in hostile environments are of broad interest. There is an ongoing need to research, develop and demonstrate low-cost multi-sensor, non-imaging sensor nodes which can be disbursed on the battlefield to classify, localize and track targets. Requirements for large numbers of personnel detection sensors demand emphasis on new inexpensive classes of sensing elements, while maintaining high system performance levels using robust signal processing and fusion algorithms, all the while being power efficient.

2.0 PROGRAM OF WORK

The SET-158 Task Group participating Nations were Canada, Denmark, Finland, France, Netherlands, Tunisia, Turkey and United States. The Task Group used three objectives to accomplish its work. The first objective was to review current and historical low-cost sensors available for personnel detection that meet the above rationale. This was accomplished using national surveys provided by participants and a review of personnel detection sensors used in the conflict in Southeast Asia. Briefly, modern sensors for personnel detection date back to the war in Southeast Asia between the years of 1956 – 1975. One principal goal was the interdiction of materiel moving on the Ho Chi Minh Trail. Sensors that were deployed during this conflict included seismic geophones, microphones, electric and magnetic sensors and radar. The target signatures of interest included human voice and footsteps and the sounds and vibrations from vehicles, electric and magnetic signatures and active radar detection. The signals received are fused at the sensor level. For example, Navy-trained sonar operators listened for voices on microphones and attempted to correlate the presence of voice signals with seismic sensors that detected the presence of footsteps. Multi-node systems consisted of strings of geophones to obtain target direction and speed along the trail. Additional strings of geophones were used to confirm the target presence at distant locations. These sensor systems included long- and short-haul radios so that the data could be poled from overhead aircraft. While high detection rates resulted, the systems were plagued by very high false alarm rates. These efforts were supported by acoustic and seismic working groups led by the Naval Air Development Center in Warminster, PA, and Sandia National Laboratory in Albuquerque, NM. The interested reader is referred to several readily available reports titled Project CHECO Report, IGLOO WHITE.

[1] Dr. Sabatier was an U.S. Army Research Laboratory, Intergovernmental Personnel Act (IPA) employee at the time this SET Panel research was conducted.

[2] Dr. Thyagaraju Damarla, RDRL-SES-A, U.S. Army Research Laboratory, Adelphi, MD 20783, USA.

Second, a review of the physics of human motion research that impacted personnel detection was accomplished. This included the historical detection approaches used in sensing mechanisms such as human voice, seismic footsteps, and the thermal and magnetic phenomenon of walking humans. This is presented in Section 5 of this report.

Third, relatively new sensing modality based on sensing micro-Doppler motion of human body appendages such as arm, leg and torso motion was exploited (see Section 4). By far the largest modeling effort was the development of the micro-Doppler velocity signatures from human limb motion. Considerable parallel modeling in the radar community is concurrently being developed, but this group focused on the ultrasonic Doppler effects of limb motion. Ultrasound provides a simple and low-cost alternative to radar for range detection of a few tens of meters.

Doppler models of this human appendage motion were developed as well as new signal processing algorithms that captured the physics of seismic footsteps, voice when present and the micro-Doppler information from walking people. Logical fusion approaches to data from multiple sensors were also developed. This is presented in Section 6.

3.0 SET-158 PROGRAMMATIC EFFORTS

To further advance these objectives, the Task Group took advantage of workshops on personnel detection that were jointly organized and conducted by the US Army Research Laboratory (ARL) and the University of Mississippi (UM) in May 15-17, 2012. ARL and UM had organized two previous human and light vehicle detection workshops prior to the onset of SET-158. The workshop focus was human detection using acoustic, seismic, and magnetic and electric field sensors and other novel sensing mechanisms. The workshop's target audience is university, industry and government scientists and engineers with expertise in sensor phenomenology, signal processing, detection and network information processing.

A NATO RTO Specialists' Meeting titled "Autonomous Sensing and Multi-Sensor Integration for ISR Applications" was held in Cardiff, UK, 24-25 October 2011. The NATO technical representatives from SET-142 TG on "Acoustics and Autonomous Sensing for ISR Applications", SET-153 TG on "Multi-Sensor Integration for Urban Operations", and the SET-158 TG on "Disposable Multi-Sensor Unattended Ground Sensors Systems for Detecting Personnel" developed this meeting to address these critical technology areas in part for personnel detection. This meeting served to bring together experts in Doppler human motion detection, signal processing and fusion for personnel detection.

SET-158 conducted task force meetings for planning and progress reporting. These gatherings led the Task Group to conduct two personnel field trials on the SW US border that were attended by national representatives from Canada, Finland and the US. Several additional groups participated in the field trial including University of Memphis, US Army Night Vision Laboratory, Ft. Belvoir, VA and SPAWAR, San Diego, CA. ARL and UM, in conjunction with University of Memphis conducted an earlier field trial on the SW border and this second field trial was a natural follow-on to the SET Panel activity.

4.0 ULTRASONIC MICRO-DOPPLER MODELING

Walking people create unique acoustic Doppler signatures that can be applied to human motion analyses. The individual body segments (foot, leg, arm, torso, etc.) have different acoustic cross-sections and velocities that form these unique human Doppler signatures. Continuous-wave ultrasound is used to measure the Doppler

shifted signal reflections from the body segments as the person moves. The reflected ultrasonic signal from the human body is Frequency Modulated (FM) by the motion of the human body segments. The acoustic cross-section of the body segment influences the amplitude of the received Doppler signal. These human motion Doppler signatures have been extensively studied using ultrasonic sonar systems.

The principle of ultrasonic Doppler sonar relies on the detection of a Doppler shift in the frequency of acoustic waves scattered by a moving target, from which a time-resolved measurement of the target velocity is obtained. The reflected FM ultrasound signal is received by the transducer that is co-located with the transmitter and can be mathematically expressed as:

$$g(t) = A\cos(2\pi f_c t + \phi(t)) \tag{1}$$

where A = amplitude of the received signal, f_c = carrier frequency, and $\phi(t)$ = instantaneous phase. It can be written as:

$$\phi(t) = \frac{4\pi}{\lambda}\int_{-\infty}^{t} \nu(t)d\tau + \phi_0$$

where $\nu(t)$ is the velocity of a moving object and can be written in terms of the Doppler frequency as in the following:

$$f_d(t) = \frac{2f}{c}\nu(t) \tag{2}$$

where c is the speed of sound.

Generation of $I(t)$ and $Q(t)$ Samples

In order to demodulate the received FM signal, the FM signal is converted into baseband $I(t)$ and $Q(t)$ by multiplying the FM signal with both the carrier signal and shifted version of the carrier signal. Mathematically, it can be expressed as:

$$g(t) \times g_c = \frac{1}{2}[\cos(4\pi f_c t + \phi) + \cos(\phi)] \tag{3}$$

where $g_c(t) = B\cos(2\pi f_c t)$ and is synthetically generated, $Q\ (t)$ samples can be obtained by using the following expression:

$$g(t) \times g_{co} = \frac{1}{2}[\sin(4\pi f_c t + \phi) + \sin(\phi)] \tag{4}$$

where $g_{co}(t) = B\cos\left(2\pi f_c t - {}^{\pi}/_{2}\right) = B\sin(2\pi f_c t)$. After performing low-pass filtering on Eqs. (3) and (4), the baseband $I(t)$ and $Q(t)$ are:

$$I(t) = \cos(\phi) \tag{5}$$

$$Q(t) = \sin(\phi) \tag{6}$$

The Doppler baseband $I(t)$ and $Q(t)$ components are decimated, to reduce the over sampling, before being added to form a complex Doppler signal as in the following:

$$S(t) = I_{dec}(t) + iQ_{dec}(t) \tag{7}$$

where I_{dec} and Q_{dec} are the decimated I and Q samples and i is the imaginary unit.

Velocity Calculation at Base Band

The velocity of human body segments can be computed using a well-known spectrogram, essentially the square of the Short-Time Fourier Transform (STFT), which can be expressed as:

$$STFT(t,f) = \int S(t+\tau)w(\tau)\exp(-j2\pi f\tau)\,d\tau \quad (8)$$

where $S(t)$ is the complex down-converted signal as given in Eq. (7), $w(t)$ is a sliding window function (e.g., a Hamming window), t is time and f is frequency. STFT can be represented as a time-frequency plot. The horizontal axis is time, the vertical axis is frequency, and the magnitude of the STFT output at each point is represented by the hue of the point's color.

4.1 Human Motion Sonar

To measure the human motion Doppler signals, the ultrasonic sonar uses commercially available, low-cost ultrasonic ceramic transducers. The sonar was assembled from two identical ultrasonic transducers: one transducer acts as a transmitter emitting an ultrasonic wave while the other acts as a receiver, sensing the echoes.

Measurements of the sound reflected from walking people using the sonar were conducted on a straight line track marked on the floor in a hallway of a modern university building. The sonar was placed on a tripod at a 1.2 m height and located at one end of the track. In the test configuration, the beam patterns of the ultrasonic transducers were oriented along the walking track and towards the walker. The person started walking at 1 m from the sonar location and walked away for about 10 seconds before stopping and turning around to walk back towards the sonar. The walking away spectrogram, or the sonar signal, is presented in Figure 1 for the Doppler signature. This sonogram is the composite Doppler motion of sound scattering from the whole of the body segments as the person walks. The horizontal line at zero Hz in the Figure 1 is the sum of direct sound coupling between the transmitter and the receiver through the air and the common enclosure and the reflected signals from stationary or zero velocity, reflecting objects. The strongest amplitude reflection from a walking person corresponds to the fluctuating line near the frequency of -300 Hz (marked as No. 1 in Figure 1) for walking away (negative Doppler shift) from the sonar. The Doppler shift, -300 Hz, is proportional to the person's speed V. The speed of the walker can be calculated from the Doppler shift equation $V = 2\, f_d / \lambda$, where V is the speed, f_d is the Doppler frequency shift and λ is the acoustic wavelength. For sound speed in air at room temperature, this results in a calculated speed of -1.3 m/s.

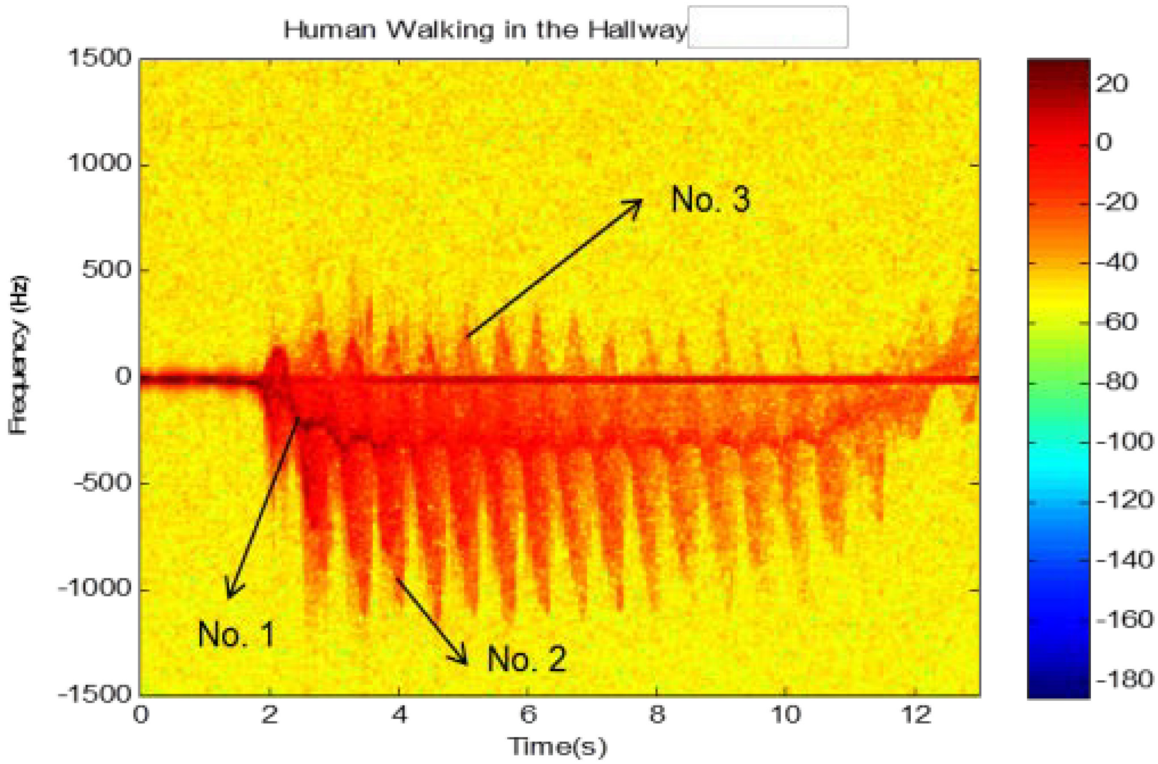


Figure 1: The Composite Doppler Frequency Response of a Person Walking: Torso, Legs and Arms Marked as Nos. 1, 2, and 3.

The envelopes of curves marked as No. 2 in Figure 1 correspond to the motions of the legs, which have smaller acoustic cross-sections than the torso and therefore have lower amplitudes. The leg's maximum Doppler shift, largest velocity (5.2 m/s), is from the foot and is three times larger than the torso velocity. The motion of the arms back towards the sonar as the person walks away from the sonar is marked as the envelope No. 3 in the figure and has a Doppler shift (hand motion) of 250 Hz or 1 m/s. The motion of other body segments results in Doppler returns that are proportional to those acoustic cross-sections and velocities. The sonar gram shown in Figure 1 is a whole composite Doppler sonogram of all of the moving body segments from which the ultrasound reflects or scatters. To further understand the Doppler contributions of the individual segments, a Fresnel-Kirchoff diffraction theory for the analysis of body segment motion was developed and is presented next.

4.2 Ultrasonic Sonar Model

The human body is represented as a segmented link system following Winter's model [1]. The Boulic-Thalmann model [2] is used to predict joint angle time histories and the temporal displacements of the body center of mass. The velocity at the proximal and distal end of each key body segment as a function of time is determined from the Boulic-Thalmann (BT) joint rotations and body translations using rigid body physics for the angular motion of the segment. Scattering is assumed to occur from seven types of body segments: the foot, lower leg, thigh, trunk, head, neck, upper arm and lower arm-hand. For the purposes of scattering, the body segments are modeled as ellipsoids. The dimensions of these ellipsoids are estimated from the segment length, mass and density. At-rest acoustic scattering cross-sections for the segments are determined using Fresnel-Kirchhoff diffraction

theory. Velocity and time dependent spectral acoustic cross sections are obtained by exploiting the fact that the velocity at points on a rotating-translating rigid body must continuously vary across its length. Doppler sonar grams are computed by mapping the time dependent spectral acoustic cross-sections of the various body segments onto time-velocity space. This mapping is implemented in a way that mimics the STFT used in the processing of Doppler sonar data.

A walk cycle consists of two steps. It begins with left foot Heel Strike (HS), continues through right foot HS, left foot Toe Off (TO) and ends with the second HS of the left foot. The stride period is the time required to take two steps. It can be related to the average velocity of walking and the body height *H.* In the BT model, the body is represented as a segmented link system in a spatial coordinate system. The center of the coordinate system is referred to as the spine center. The lower body is free to rotate in three directions (roll, pitch and yaw) about the spine center. The torso is free to rotate about the spine center independently of the lower body. Flexion occurs at the hip, knee and ankle for the right and left legs. Flexion also occurs at the shoulder and elbow for the right and left arms. Left- and right-side leg and arm motions are symmetrical. Additionally, the body translates about spine center. In total there are twelve degrees of freedom.

The model assumes a measurement geometry in which an individual is walking directly toward the sonar – as described in the hallway measurements. This geometry maximizes the Doppler sonar’s response to sagittal plane swinging motions of the legs and arms as well as sagittal plane motions of the trunk. When the body is in motion, the motion induced scattering effects include the assumption that the segment moves like a rigid body and the linear velocities of scattering centers along a segment length can be computed for simple rational dynamics and the time derivative of the BT joint angle time function. **The real value of this approach is that it allows for the signal received from each segment to be modeled.**

Figure 2(a) shows the contribution to a Doppler sonar gram from the right foot for an individual walking toward the sonar at a speed of 1.3 m/s. Heel strike of the left foot occurs at about 1.1 s. At this time both feet are in contact with the ground and the velocity is zero. Following left HS, the right foot swings forward producing the wide range of velocities seen between 1.25 and 1.5 s. During this time interval there are substantial differences between the velocity of the ankle and the toe. These differences produce the velocity spreads at individual times in the gram in accordance with rigid body rotation. Also shown in Figure 2(a) is the contribution of the torso. The torso contribution to the gram occurs in a very narrow velocity band due to the small differences between the velocity of the spine center and base of the neck (proximal and distal segments for torso). This velocity oscillation is caused by accelerations of the body center of mass resulting from two heel strikes and toe offs and is twice the gait frequency.

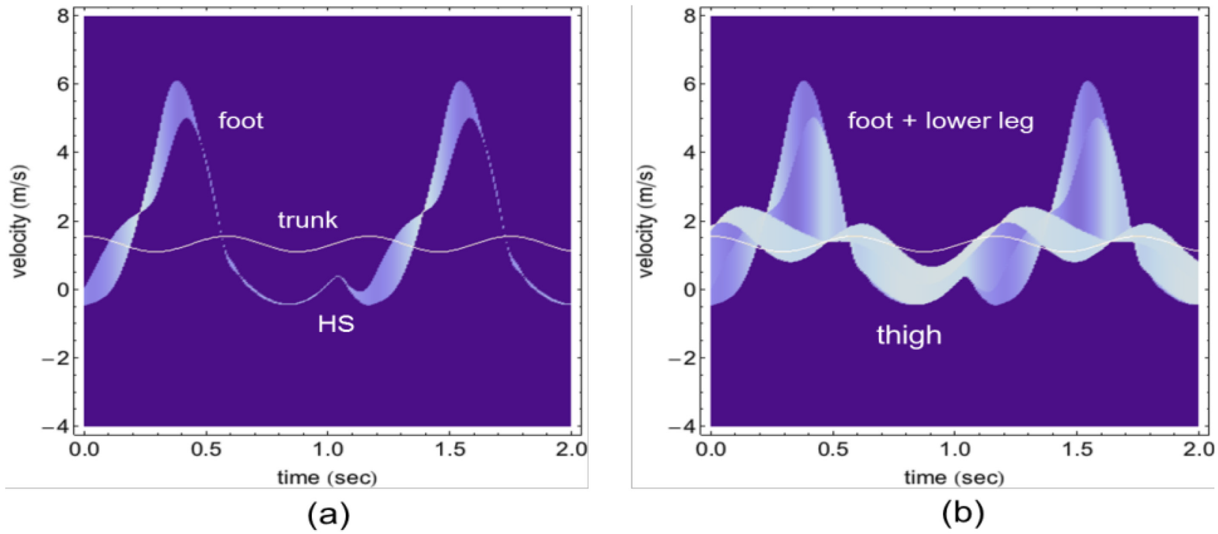


Figure 2: (a) Velocity of Foot and Torso; (b) Adds the Lower Leg and Thigh.

Figure 2(b) shows the additional contributions to the Doppler sonar gram from the right lower leg and thigh. The contribution to the sonogram from the thigh occurs at low velocities similar to those of the torso but with a broader overall spread in velocity and weaker energy levels due to the smaller relative size of the thigh in comparison to the trunk. The return from the lower leg fills in the region between the return from the foot and thigh. Its amplitude is stronger than that of the foot and is most pronounced when the lower leg is perpendicular to the ground and normal to the transducer. At these times the lower leg presents maximum acoustic cross-section to the sonar. The torso by way of contrast always presents maximum acoustic cross-section to the sonar provided that the individual is walking directly toward or away from the sonar.

4.3 Selected Sonar Publications

M. Bradley and J.M. Sabatier, "Distinguishing Between Human and Equine Motion Using Micro Doppler Sonar", Journal Acoustical Society of America Express Letters EL-11-1567, May 2012.

M. Bradley and J.M. Sabatier, "Acoustically-Observable Properties of Adult Gait", Journal Acoustical Society of America Express Letters, EL-11-1536, 2011.

M. Bradley and J.M. Sabatier, "Aerial Ultrasonic Micro Doppler Sonar Detection Range in Outdoor Environments", Journal Acoustical Society of America Express Letters, EL-11-1512, 2011.

M. Bradley and J.M. Sabatier, "Applications of Fresnel-Kirchhoff Diffraction Theory in the Analysis of Human-Motion Doppler Sonar Grams," Journal Acoustical Society of America Express Letters, Vol. 128, pp. 1-10, November 2010.

A. Mehmood, J.M. Sabatier, M. Bradley and A. Ekimov, "Extraction of Walking Human's Body Segments Using Ultrasonic Doppler", Acoustical Society of America Journal, Vol. 128, p. 316, 2010.

S.G. Benka, "Doppler SONAR in Air for Border Security", Editor-in-Chief, Physics Today June 2012, http://scitation.aip.org/content/aip/magazine/physicstoday/news/10.1063/PT.4.0401.

5.0 FIELD TRIAL: DATA COLLECTION AT A US SOUTHWEST BORDER

In March 2012 several Nations and universities participated in data collection at a US southwest border in order to develop robust, model-based algorithms for personnel detection. The selection of the site for data collection is done to get real data in an open environment where the algorithms might be used to solve the problems faced by the US Department of Homeland Security. The site is selected because the border security personnel are faced with actual encounters with people crossing the US border illegally. Some other considerations involved in site selection are:

a) Different terrains (for example, hard tracks and soft sand river bed used by the trespassers);

b) Environmental diversity; and

c) Wildlife (which causes false alarms on fielded sensors), etc.

The participants of the data collection are listed below:

1) US Army Research Laboratory (ARL), Adelphi, MD 20783, USA.
2) Night Vision, Ft. Belvoir, VA, USA.
3) SPAWAR, San Diego, CA, USA.
4) University of Mississippi, Oxford, MS, USA.
5) University of Memphis, Memphis, TN, USA.
6) Canadian Defence Organization.
7) Israeli Team.
8) Finnish Defence Organization.

5.1 ARL Data Collection System

ARL has brought three sensor systems which are used to collect the data for the choreographed scenarios. It also brought another three sensor systems to collect data of animals in their natural habitat; the data is collected day and night. The sensor systems are:

1) Wavebook data collection system is primarily used for data collection for choreographed scenarios where people and animals walked along the trails in an orderly fashion. It has 8 channels for data acquisition. The sampling rate, and the aliasing filters can be pre-programmed as desired. The following sensors are used on the Wavebook:
    - Acoustic;
    - Seismic;
    - Passive Infrared (PIR); and
    - Ultrasonic sensor suite.

2) Automatic data collection unit is used at remote sites to collect the data round the clock for animals in their natural habitat. The system is capable of collecting data on 8 channels at 4 k samples per second. The sensor suite consists of:
    - Acoustic;

- Seismic;
- PIR; and
- Ultrasonic sensor suite.

The sensors – acoustic, seismic, PIR and ultrasonic – used for data collection are the same as the ones used during the 2009 data collection. The Wavebook data collection system with the sensor suite deployed is shown in Figure 3 and Figure 4 shows one of the scenarios being enacted during the data collection. Figure 4 clearly shows several people and animals walking the trail.

(a) (b)

Figure 3: (a) ARL Sensor Deployment; (b) New Profiling Sensor.

Figure 4: People and Animals Walking on the Trail.

5.2 Night Vision Data Collection System

Night Vision, Fort Belvoir, VA, has brought a high-resolution camera to the field to collect data. The camera system is shown in Figure 5. The system included a fisheye to see the targets coming from all around.

Figure 5: Night Vision Camera System.

5.3 SPAWAR Data Collection System

SPAWAR has brought two magnetic sensors and deployed them along the trail. The sensor is sensitive enough to detect people passing by carrying some ferrous material (for example, keys). The sensors are shown in Figure 6.

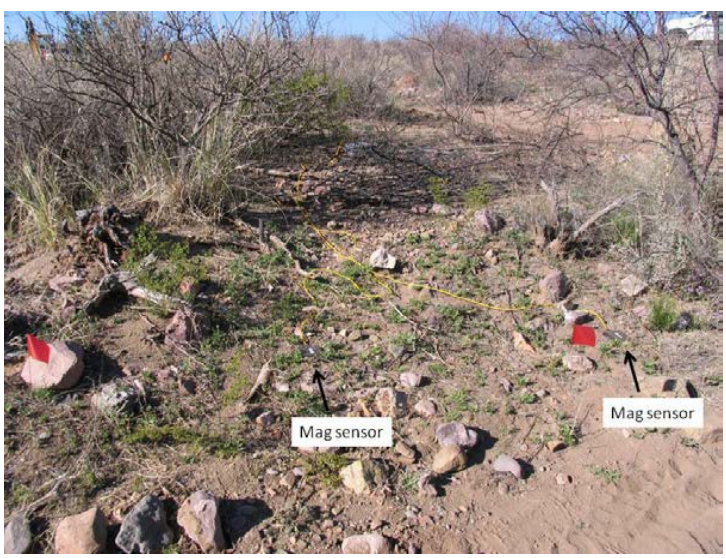


Figure 6: SPAWAR's Magnetic Sensors.

5.4 University of Mississippi Data Collection System

University of Mississippi has deployed a similar system to that of ARLs with acoustic, seismic and ultrasonic sensors. The deployed system is shown in Figure 7.

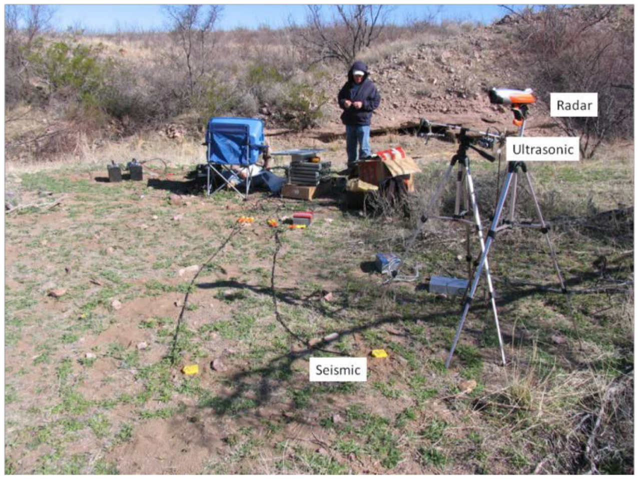


Figure 7: University of Mississippi Sensors.

5.5 University of Memphis Data Collection System

The University of Memphis had been working on developing a new sensor system to replace high power consuming, high bandwidth requiring imaging sensors such as a camera. They have developed a pyro-electric array profiling sensor with fewer pixels to capture the essence of an image. The deployed sensor is shown in Figure 8.

Figure 8: Profiling Sensor by University of Memphis.

5.6 Defence Research and Development Canada SASNet

The Canadian Defence Organization has developed a low-cost network called "Self-healing Autonomous Sensor Networks (SASNet) for detection and tracking of targets. Each sensor node in the SASNet consists of acoustic, seismic and magnetic sensors. Figure 9 shows some elements of SASNet.

Figure 9: SASNet.

5.7 Israeli Team

The Israeli team has deployed their system called "Pearls of Wisdom" consisting of acoustic, seismic, magnetic and imaging sensors. Their system is shown in Figure 10.

Figure 10: Pearls of Wisdom.

6.0 SIGNAL PROCESSING

In this section, we present some of the advances made in seismic and ultrasonic signal processing for personnel detection. Most of the advances in signal processing concentrated on acoustic (ultrasound) and seismic sensors as they offer high fidelity to distinguish people from animals.

6.1 Seismic Signal Processing

The main purpose of a seismic sensor is to detect footfalls of humans walking within the receptive field of the sensor. There is a considerable amount of literature [3], [5] in footstep detection. Traditionally, researchers have focused on estimating the cadence. However, if multiple people are in the vicinity of the sensor and walking, it is difficult to estimate the cadence of an individual person. Moreover, if there are animals, it is difficult to differentiate multiple people walking and animals walking by observing the footfalls. However, multiple footfalls superimposed on one another, resulting in a frequency of 'c' Hz (where 'c' is an effective cadence of multiple walkers). So, a seismic algorithm can look for harmonics of cadence or several strong frequency components between 2 to 15 Hz to distinguish single and multiple walkers.

The seismic algorithm used is a multivariate Gaussian classifier [4] with the feature set consisting of amplitudes of the frequency bins from 2 to 15 Hz. Then the algorithm is used to estimate the posterior probability of footsteps present.

The algorithm only determines whether there are footsteps present. In order to detect the presence of humans, it is necessary to determine whether these footsteps belong to a human or an animal. For this, we invariably turn to acoustics. If there is voice, it can be detected and identified as a human voice based on the formants. In order to distinguish people and animals when no voice is present, we analyze the sound generated by the animals walking. When a single hoof of a horse strikes the ground, it produces a sound pattern that is distinct from that of a human foot. Figure 11(a) shows the signature of a horse walking (for a period of 6 s) before and after noise removal. The noise removal is performed using empirical mode decomposition of the original signal into various component signals. From Figure 11(b), it is clear that there are three peaks uniformly distributed in each time interval of one second. This indicates the cadence of the horse to be approximately 2.8 to 3 Hz. Since the cadence of a person is around 1.5 to 2 Hz, one can infer the presence of animals.

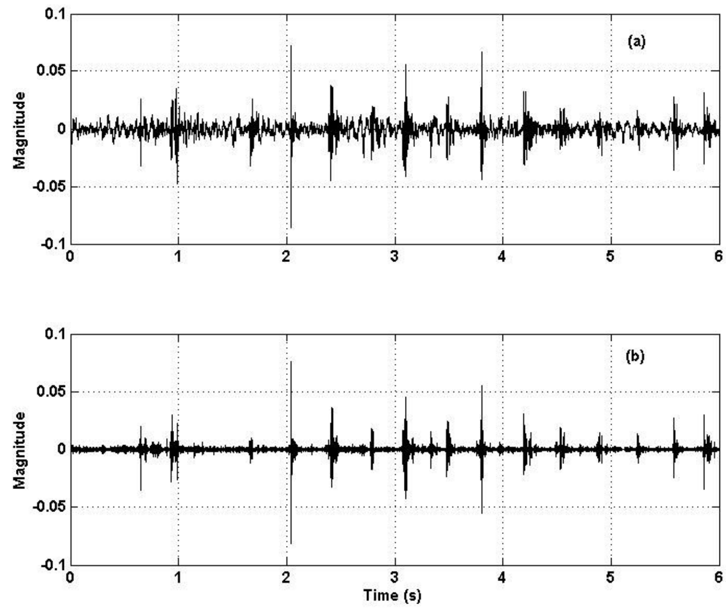


Figure 11: (a) Hoof Signature; (b) Hoof Signature After Noise Removal.

When a person walks, the heel of the foot strikes first and then the toe end of the foot strikes, rubbing against the ground, creating a unique seismic signature compared to that of an animal (see Figure 12) Animals, in general, walk on their hoof or "toe" (the horse ankle and heel or fetlock do not strike the ground), which strikes the ground producing signatures that are different from those of people. Both the signatures have different frequency responses on the same ground. In Section 6.2, we present a technique that uses the differences in frequency responses to distinguish both types of footfalls.

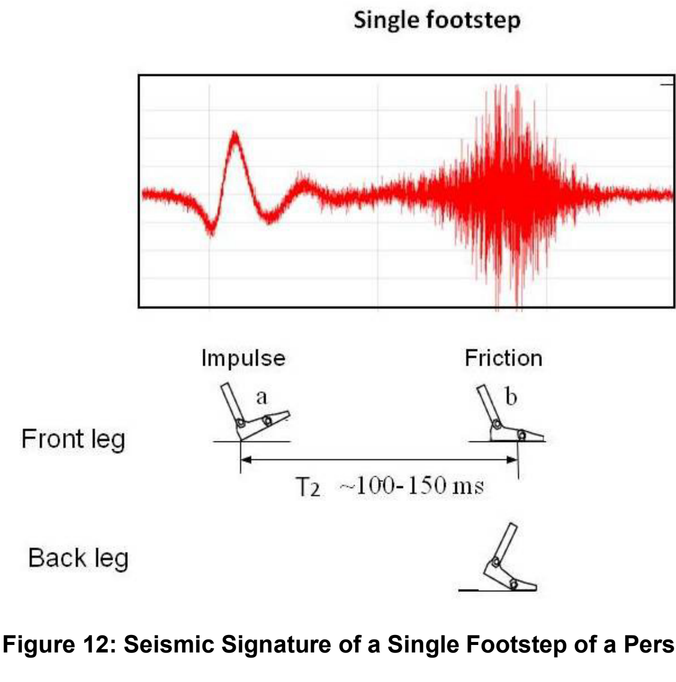


Figure 12: Seismic Signature of a Single Footstep of a Person.

6.2 Discrimination of Animal and Human Seismic Signatures

For a single walking person, detection of cadence and human footstep signature is relatively easy. However, when animals and people are walking in the vicinity of a seismic sensor, the detection of human foot signature is not as straightforward. If there are multiple sensors collecting the same signatures, one can use the Principal Component Analysis (PCA) or Independent Component Analysis [6] (ICA) to separate the human footstep signatures from the animal footsteps depending on whether the noise is Gaussian or not. Most of the Unattended Ground Sensor (UGS) systems consists of only one sensor per modality, that is, one acoustic, one seismic, etc., so it is not possible to use the PCA or ICA technique for signal separation, since PCA or ICA requires at least '*n+1*' number of sensors to separate '*n*' sources. In acoustics, several researchers [7] have developed techniques for single channel source separation where they attempted to separate signals from two human speakers from a single microphone. In almost all the cases, they used Short Time Fourier Transform (STFT) and Non-negative Matrix Factorization (NMF) techniques.

The NMF technique was first introduced by Lee and Seung [8] and was adopted by others to minimize the cost function:

$$\frac{1}{2}\sum_{w,t}\left\| X_{w,t} \right| - \sum_{k} H_{w,k} W_{k,t} \Big|^{2} + \lambda \sum \left| W_{k,t} \right|^{1} \tag{9}$$

where X is the STFT with variables in frequency w and time t, H and W are the basis and weight matrices, and λ controls the sparcity of the weights, that is, fewer weights, hence fewer basis functions, will be used. The fact that the elements of $X_{w,t}$, H and W are all non-negative gives the algorithm the name non-negative matrix factorization. We use Discrete Cosine Transform (DCT) instead of STFT to avoid the problems arising due to complex signals. Let:

$$X_i = dct(x_i(t)) \tag{10}$$

be the DCT of the signal $x_i(t)$. It is found that the first 500 of the DCT coefficients are sufficient to reconstruct the time domain signal with negligible distortion. It is worth noting that earlier versions of JPEG compression schemes used DCT. So X_i denotes the first 500 DCT coefficients. Let B_i and β_i denote the positive and negative DCT coefficients such that $X_i = B_i - \beta_i$. Let the matrix $X_p = \{X_i\}; \quad \forall i$ be the set of DCT coefficients for all the training data corresponding to the people. Then, the matrix $[X_p]$ can be written as:

$$[X_p] = [X_p^+] - [X_p^-]$$

with matrix $[X_p^+] = \{B_i\}$ representing the positive DCT coefficients and matrix $[X_p^-] = \{\beta_i\}$ representing the negative DCT coefficients of X_p. Similarly, X_a represents the set for animals. After performing the NMF on the matrices, we get:

$$\left[X_p^+\right] \approx W_p H_p; \quad \left[X_p^-\right] \approx \mathbf{W}_{\mathrm{p}}\,\mathbf{H}_{\mathrm{p}}$$

$$\left[X_a^-\right] \approx W_a H_a; \quad \left[X_a^-\right] \approx \mathbf{W}_{\mathrm{a}}\,\mathbf{H}_{\mathrm{a}}$$

The matrices W and $\mathbf{W}$ represent the weight matrices and the matrices H and $\mathbf{H}$ correspond to the bases. Once the basis matrices are available, they can be used to represent the DCT coefficients X_t of a test signal $x(t)$ as the weighted sum of their components. The algorithm to estimate the weights and bases (subset of H and $\mathbf{H}$) is given below.

Algorithm 1:

- Step 1: Normalize the test signal $x(t)$ after removing the mean. Compute X_t = dct ($x(t)$). Let $X_t = B_t - \beta_t$, where B_t and β_t denote the positive and negative DCT coefficients.
- Step 2: Estimate the weights $W = \{w_1, w_2, \cdots, w_r\}$ and $V = \{v_1, v_2, \cdots, v_r\}$ such that:

$$|B_t - WH|^2 + |\beta_t - V\,\mathbf{H}|^2 \text{ ; such that } 0 \le \omega_i, v_i \le u_b; \forall i \in \{1, 2, \cdots, r\} \tag{11}$$

is minimum, u_b is typically 1. One may use any constrained non-linear optimization program such as the "*fmincon*" function in MATLAB to determine the weights:

- Step 3: Non-zero weights ω and v give the bases used to represent X_t.
- Step 4: Reconstruct the signal $\hat{x}(t)$ by taking the inverse DCT of the difference ($\omega\, H - \mathrm{V}\, \mathbf{H}$).

We used the NMF technique to separate human and animal signatures from a single seismic channel data. In order to verify the technique, we took two seismic signals, one from a person and another from a horse walking, and mixed them as shown in Figure 13. Then we used the NMF technique on the mixture to separate the signals. The results of the NMF technique are shown in Figure 14 and Figure 15. From these figures we notice the reconstruction (separation) of the signals is good except in the places where there is noise.

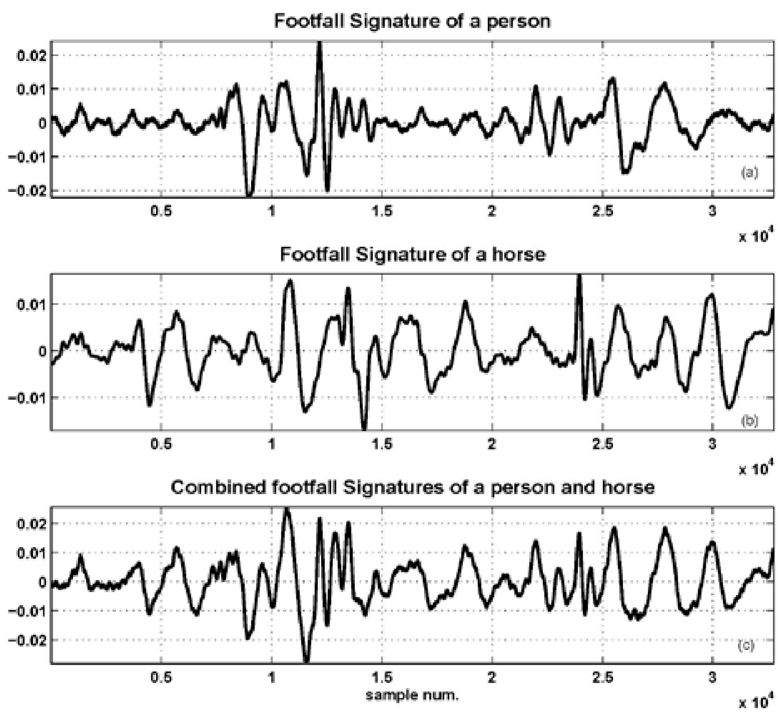


Figure 13: Mixture of a Signature from a Person and a Horse.

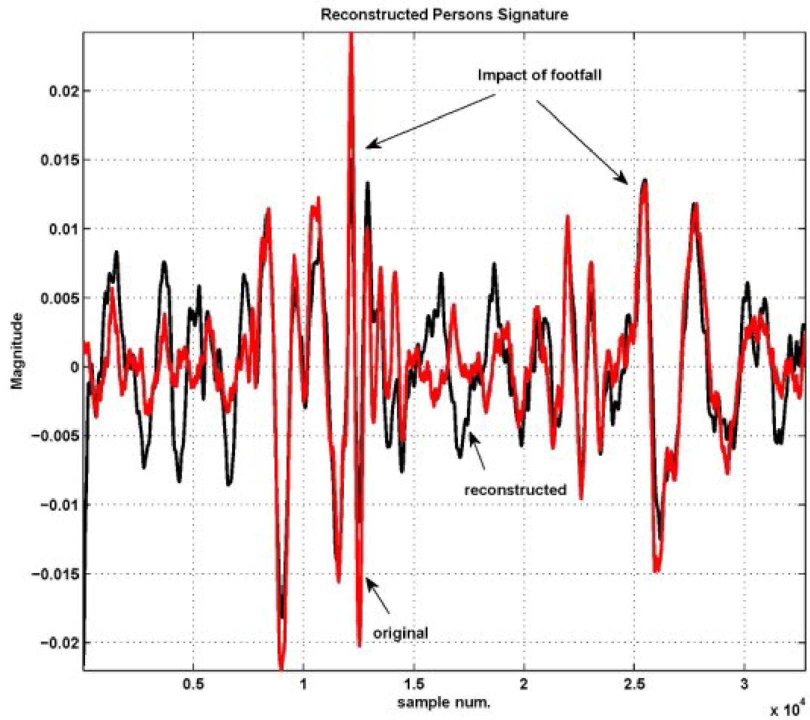


Figure 14: Extraction of Human Signature.

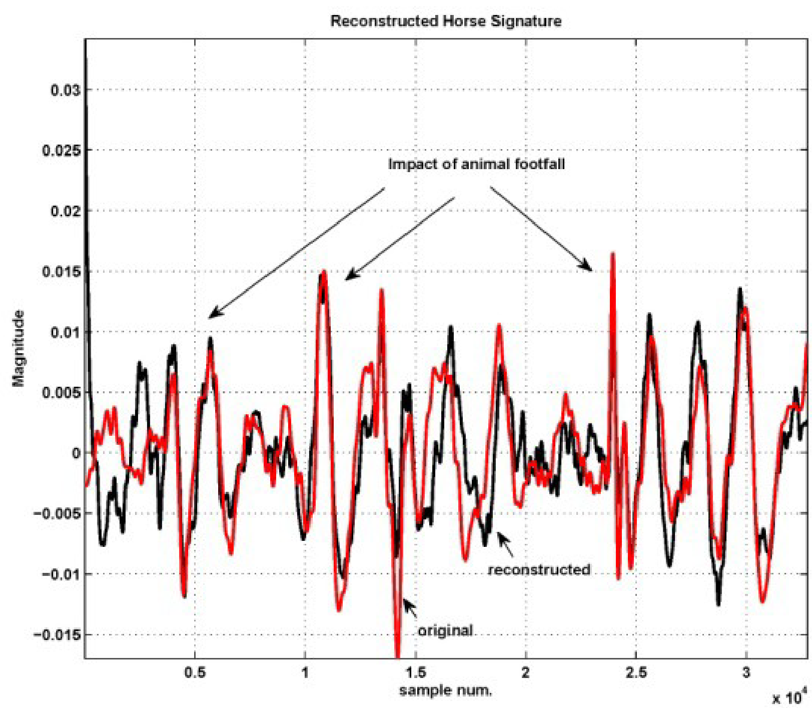


Figure 15: Extraction of Horse Signature.

The NMF algorithm is further used on several sets of data collected on a single person, single horse, and both a horse and a person walking. The sum of the weights corresponding to the bases of horse Sh and a person Sp determine whether the extracted signature belongs to a horse (animal) or a person depending on whether Sh > Sp. The values of Sh and Sp are plotted in 16 as 'o' and '*', respectively. From the figure we find that the NMF algorithm provided Sp > Sh and is higher than the threshold shown by a solid line at 0.7 for the data with one person walking majority of times and Sh > Sp for the case when a horse was walking. When both a person and a horse walked, both Sh and Sp are above the threshold, indicating that both the targets are present. So we can detect and classify the footprint signatures of people and animals even when both are present at the same time. Traditional classification algorithms classify only any one of the targets present but not both simultaneously. They fail if both targets are present.

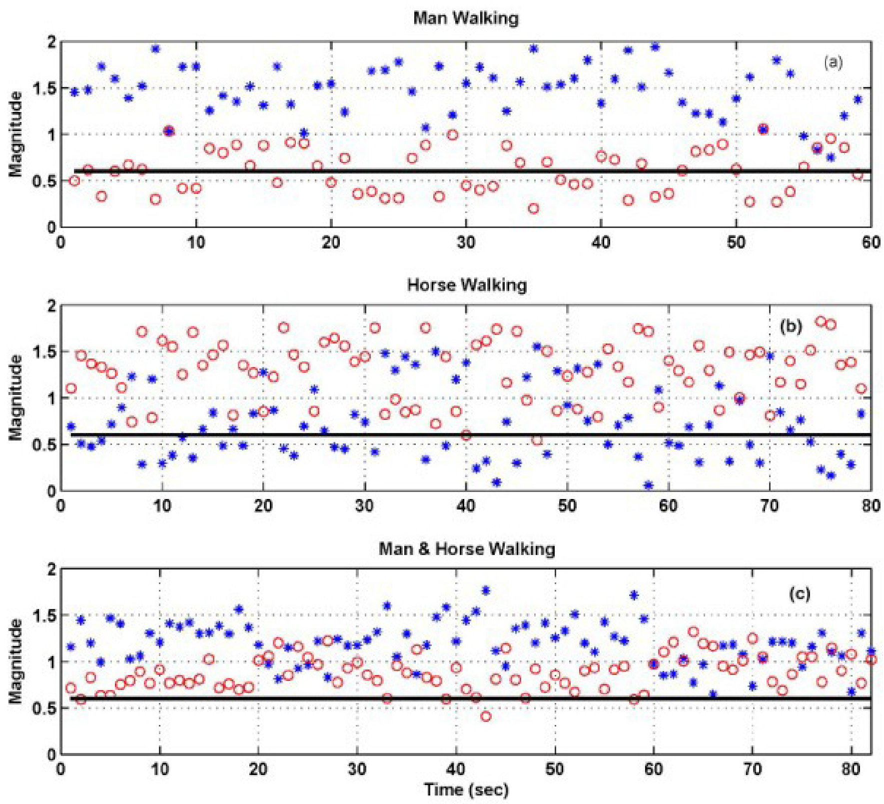
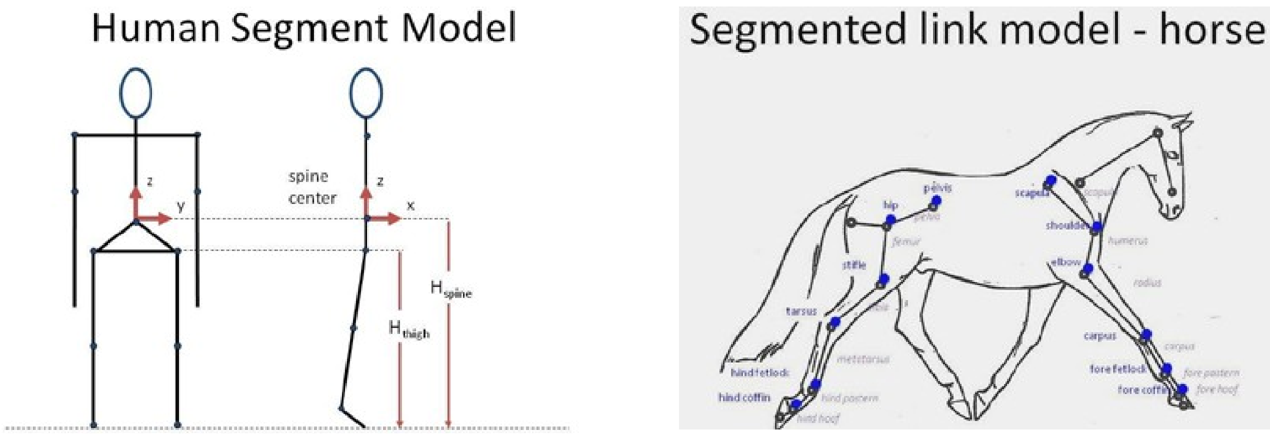


Figure 16: Results of NMF Algorithm on Signature Data of (a) Man, (b) Horse, and (c) Man and Horse Walking.

6.3 Ultrasonic Sensor Modeling and Ultrasonic Signal Processing

In this section, we present the analysis of ultrasonic sensor data to characterize and discriminate both people and animals. This is an active sensor that radiates a 40-kHz ultrasonic signal and captures the signals that are bounced back by the target in its beam. The principle of operation is same as radar [10]. The micro-Doppler returns due to the swinging of the arms, legs, and torso of a person or an animal are analyzed. We take advantage of these Doppler returns from the limbs to classify the targets. However, in order to understand the type of Doppler signatures that would be generated by the swinging of arms, legs, and torso of various targets, it is necessary to model these parts and compute the Doppler values.

Our University of Mississippi partners Bradley and Sabatier [9] have explained the observed human-gait features in Doppler sonar grams by using the Boulic-Thalmann (BT) model [2], shown in Figure 17, to predict joint angle time histories and the temporal displacements of the body's center of mass. In the BT model, body segments are represented as ellipsoids. Temporally dependent velocities at the proximal and distal end of key body segments are determined from the BT model, as shown in Figure 18. Doppler sonar grams are computed by mapping velocity-time dependent spectral acoustic cross-sections for the body segments onto time-velocity space, mimicking the STFT used in Doppler sonar processing. Figure 19(a) shows the estimated velocities using the model for various parts of the body for a 6-foot-tall person.



(a) (b)

Figure 17: (a) Human Model as a Stick Figure and (b) Horse Model.

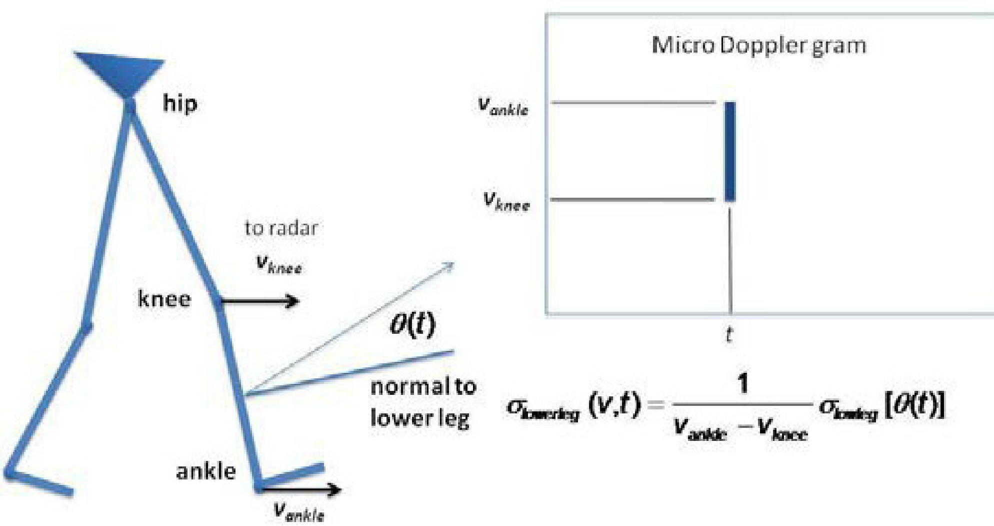


Figure 18: Estimation of Velocities of Various Parts of Body.

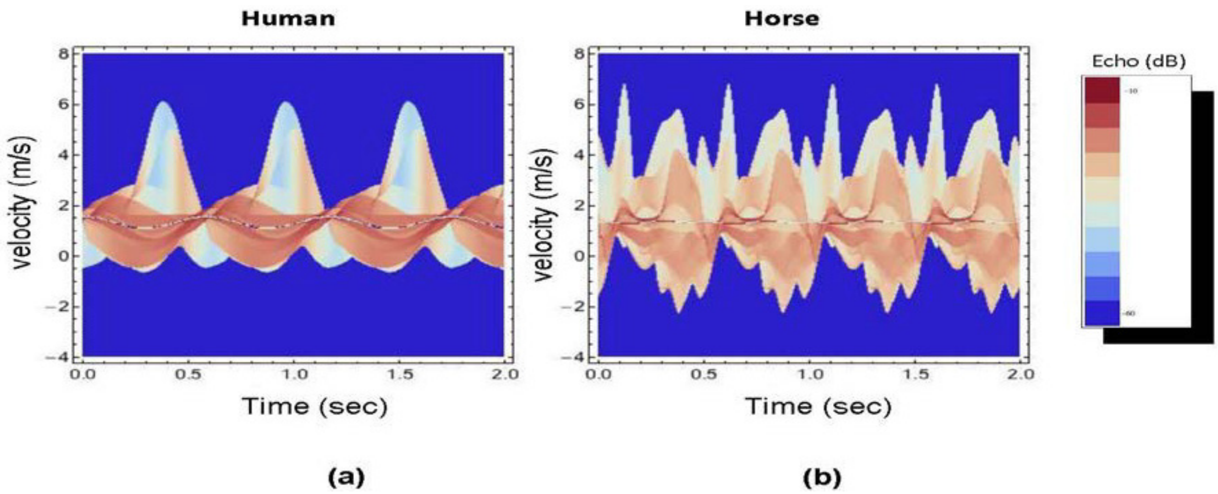


Figure 19: Estimated Velocity (Doppler) for (a) a Person Walking and (b) a Horse Walking.

The Doppler is related to the radial velocity v_r of the target and is given by $f_d = \frac{2v_r}{c} f_c$, where c is the propagation velocity of sound and f_c is the radiated carrier frequency. The detailed computation of velocities of various limbs can be found in [9]. Similar, models are developed for a quadruped [11], such as a horse. Figure 19(b) shows the estimated velocities for a horse.

Figure 20 shows the Doppler signature collected for a person walking in one of the scenarios. Each sensor records the data when the person walks by the sensor. The data collection is done when a person (or a horse) walks towards the sensor at close range (Figure 20(b)) and when the person (or a horse) walks away from the sensor at a distance and to one side of the sensor (Figure 20(c)). In the first case, the signal strength is high and the Doppler returns from the various parts are clearly visible, while in the latter case the Doppler returns are weak and the features are not clearly visible. Hence, we developed two algorithms to classify the targets, namely:

a) When the Signal-to-Noise Ratio (SNR) is high (> 6 dB); and

b) When the SNR is low.

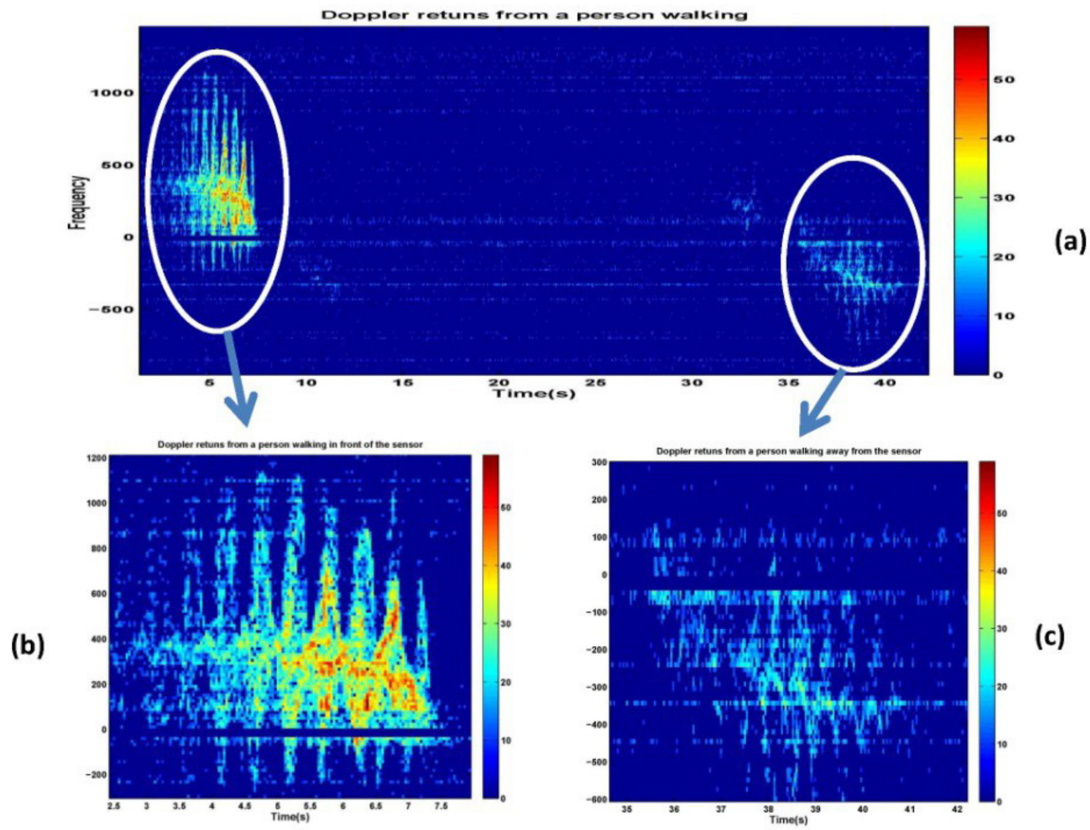


Figure 20: (a) Doppler Returns for a Person Walking, (b) Measured Doppler when a Person Walks Towards the Sensor and (c) Doppler Returns when a Person Walks Away from the Sensor.

Case 1: High Signal-to-Noise Ratio (SNR)

In this case, the targets walk in front of the sensor at a close proximity, and the atmospheric (wind) effects on the received signal are minimal. This is the case where some model features can be clearly identified, and the classification can be made based on the model. An example of high SNR is shown in Figure 20(b). In order to characterize the target either as a person or an animal, we look for:

a) Cadence;

b) Maximum and minimum variation in the Doppler frequency due to limbs; and

c) The sequential nature of limb movements.

Figure 19 shows the enlarged version of Figure 20(b). It shows the average Doppler of the torso (average velocity of a person walking) and the Doppler due to arms and legs. When the arms and legs swing forward/ backward, we get a Doppler above/below the average (the sinusoidal line above/below the average line). The cadence is estimated as 1/*t,* where *t* is the time between two peaks of a sinusoidal curve. The cadence is estimated to be 1.8 Hz for the person. The maximum and minimum Doppler frequency of limbs with respect to the average is found to be ±800 Hz, and this will be contrasted with the values for an animal. The vertical lines on Figure 21 are drawn to show the lag (sequential nature of limb movement) between the top and lower sinusoidal curves. The lag is ~ 0.1 s.

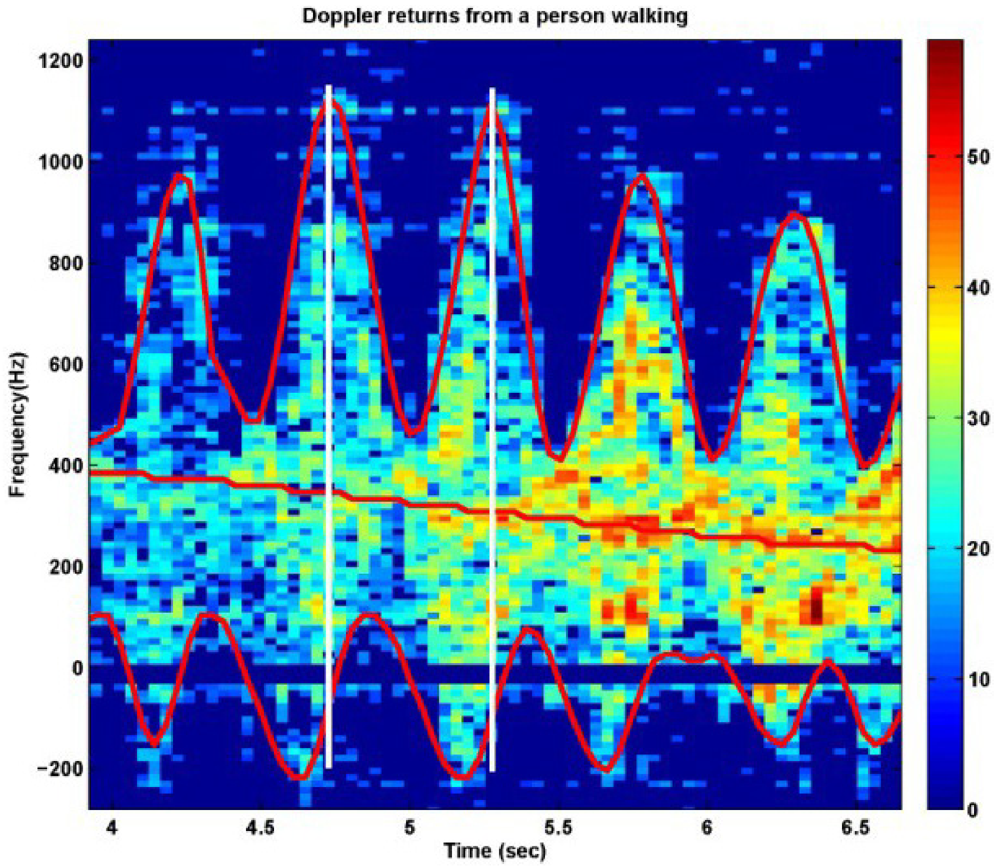


Figure 21: Measured Doppler Output for a Person.

Figure 22 shows the ultrasonic returns from a horse walking. One clear distinction between the Doppler signatures for a person and a horse walking is that the signature for a person is sinusoidal in nature. Horse motion is much more complex, as there are many more moving parts for a horse than a person. Another distinct feature for the horse is that the Doppler below the average torso Doppler is significantly less. The maximum variation of Doppler for the horse (~1500 Hz) is higher compared to that for a person (~1100 Hz). Figure 23 shows the Doppler energy plot for a horse walking. The peaks in Figure 23 show the periodic nature of a horse walking; the cadence can be estimated from it. The cadence of the horse is estimated to be around ~1.7 Hz. This cadence value is significantly low for a horse because the horse is made to walk slowly on purpose. This is also verified using the seismic data. The cadence of the horse is close to the cadence of a person walking. Hence, cadence alone cannot be used to distinguish a person from a horse or any other quadruped. From Figure 23, we notice that each peak has an adjacent smaller peak marked by ellipses in the figure. This double peakedness is characteristic of a quadruped walking and is also seen in the model shown in Figure 19(b). The time difference between two adjacent peaks is ~0.12 s. The algorithm to distinguish people and animals using the features described earlier is given in the flowchart shown in Figure 24.

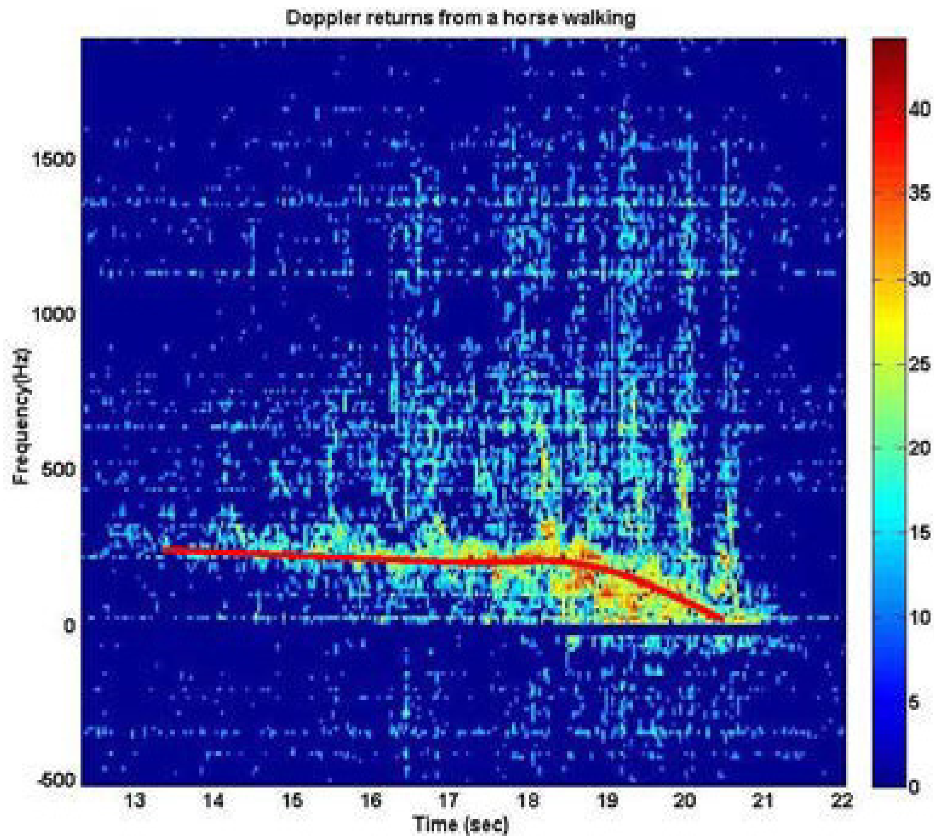


Figure 22: Measured Doppler for a Horse.

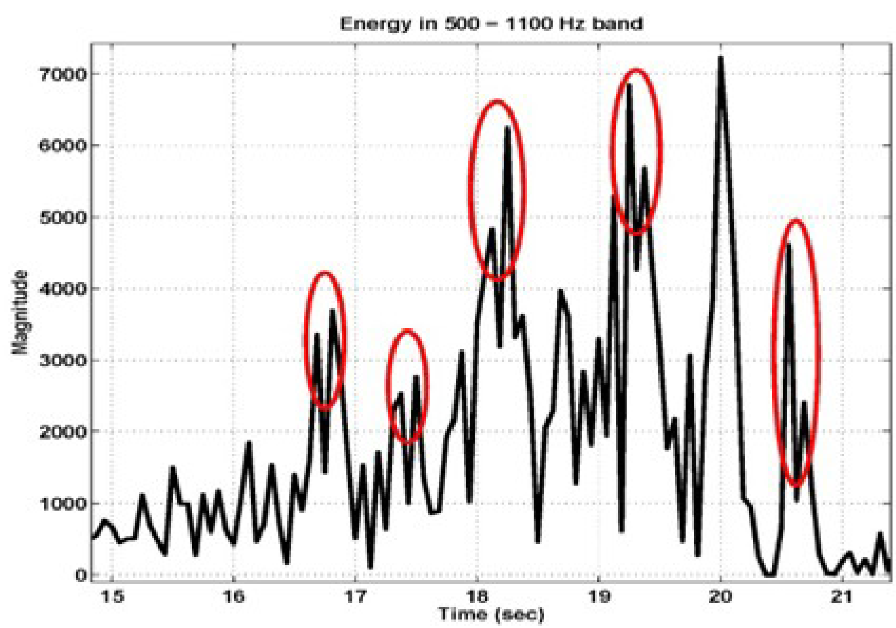


Figure 23: Doppler Energy in 500 – 1100 Hz Band for a Horse Walking.

Figure 24: Classification of Ultrasonic Data.

Case 2: Low Signal-to-Noise Ratio

In the event the signal returns are weak for any reason (such as prevailing winds, the target being farther than optimal distance, the target being illuminated by the ultrasonic transducer at an angle, etc.), the features observed in the case of high SNR may not be present as seen in Figure 20(c). For low SNR data, it is appropriate to use classical signal processing techniques to classify the targets. We used a support vector machine for classification, as shown in Figure 23.

6.4 Selected Publications

1) T. Damarla, M. Bradley, A. Mehmood and J.M. Sabatier, "Classification of Animals and People Ultrasonic Signatures", IEEE Sensors Journal, Vol. 13, No. 5, pp. 1464-1472, May 2013.

2) A. Mehmood and T. Damarla, "Kernel Non-Negative Matrix Factorization for Seismic Signature Separation", Journal of Pattern Recognition Research Vol. 8, No. 1, pp. 13-25, June 2013.

3) S. Bahrampour, A. Ray, S. Sarkar, T. Damarla and N.M. Nasrabadi, "Performance Comparison of Feature Extraction Algorithms for Target Detection and Classification", Pattern Recognition Letters, June 2013.

4) A. Mehmood, T. Damarla and J.M. Sabatier, "Separation of Human and Animal Seismic Signatures Using Non-Negative Matrix Factorization", Pattern Recognition Letters Vol. 33, Issue 16, pp. 2085-2093, December 2012.

5) T. Damarla and L. Kaplan, "A Fusion Architecture for Tracking a Group of People using a Distributed Sensor Network", Proc. ISIF Fusion 2013 Conference, Istanbul, Turkey, July 2013.

6) T. Damarla and A. Mehmood, "Detection of Targets Using Distributed Multi-Modal Sensors with Correlated Observations", Proc. IEEE Sensors Conference, Baltimore, MD, USA, November 2013.

7) T. Damarla, R. Frankel, H. Vu, M. Thielke, A. Mehmood, J. Sabatier and G. Chatters, "Personnel Detection at a Border Crossing – An Exercise", ARL Tech Report September 2013.

7.0 SUMMARY

SET-158 accomplished three main tasks. First, this includes a significant multi-modal, multi-national data collection exercise was conducted at the southwest border of the US. Second, physics based models of the micro-Doppler motion of human and animal appendages were developed. Thirdly, new signal processing approaches to the Doppler data were developed and these data were fused with other sensing modalities. All of the research accomplished has been extensively published in peer-reviewed journals.

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14. Abstract

The Sensors and Electronics Technology (SET) SET-158 committee accomplished several tasks beginning with a historical review of unattended ground sensors dating back to the beginning of the Southeast Asia conflict. Field trials were conducted on the southwest border of the US that allowed for collection of data. Signal processing and fusion models were developed and applied using the field trial data.

SET-158 met on numerous occasions beginning with the initial kick-off meeting held at the Research and Technology Organization (RTO) Office in Paris during the Spring of 2010. The committee organized personnel detection workshops that were held in the US. Both of these were in conjunction with the US Army Research Laboratory (ARL). SET-158 co-sponsored a technical meeting with SET Task Group (TG) 153 and SET-TG-142 in Cardiff, Wales, on 11 October 2011. These activities were well attended with numerous papers on personnel detection being presented. More than a dozen peer-reviewed papers have been published as a result of the committee activities and the list of these papers continues to grow.

An international data collection field exercise held in March of 2011 on the southwest US border was well attended by participating Nations. The primary objectives of the field trial were to provide opportunities for testing of commercial systems and the collection of phenomenological data using early stage developed non-imaging sensors. Several state-of-the-art, low-cost, non-imaging sensors systems were deployed on two types of ground conditions. This included ARL multi-modal sensors, video and acoustic sensors from the Universities of Memphis and Mississippi, SASNet from Canada, video from Night Vision Laboratory and Pearls of Wisdom system from Israel operated in conjunction with ARL personnel. This report summarizes the activities of SET-158.

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